Moving Forward to Module-Level Power Optimization

White Paper

Objective

Just like people require individual attention to work at their best individual capacity, so do modules. Only if a module receives the optimum specific combination of voltage and current will it work to achieve maximum performance. Through both technical discussion and the analysis of real-life data, this paper will demonstrate how additional energy can be gained from solar PV systems when applying power optimization at the module level. It is the purpose of this paper to prove that the added energy gained is significant and relevant to every possible scenario in the world of PV.

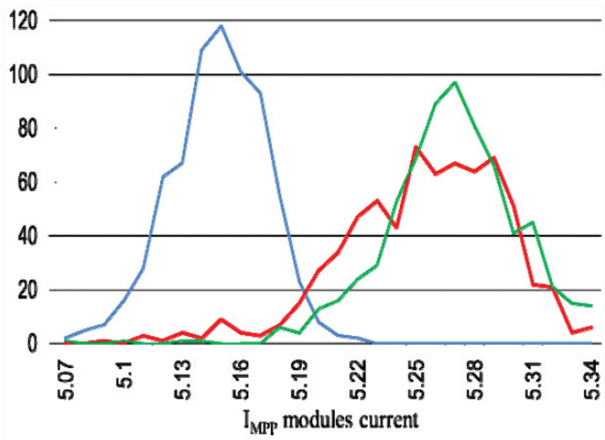
Mismatch And Traditional Inverters

Mismatch occurs when modules in an array do not exhibit fully identical electrical properties or when exposed to different environmental conditions. In fact, mismatch is a natural state existing between PV modules from their outset (figure 1). It is common knowledge that each module provides maximum power (Pmpp) at a different combination of current (Impp) and voltage (Vmpp) (figure 2).

Gaussian distributions Impp of three different production batches of the same module

Figure 1:

In his research Paolo Perotti gives witness to an effort to reduce the mismatch between over 2,800 modules during the construction of an 815 kWp PV plant in Modena, Italy. Modules were then sorted from scratch on-site based on flash-test reports. The figure shows three different Gaussian distributions of Impp to three different production batches of the same module.



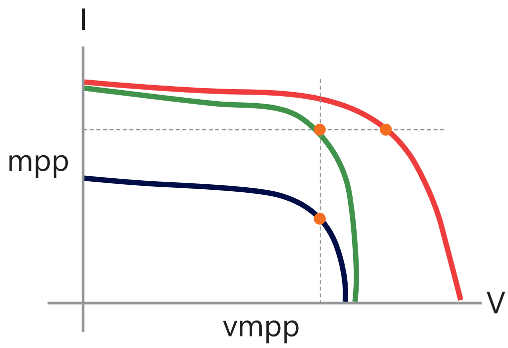
Source: P. Perotti et. al., “Monitoring and evaluation of economic impact in the reduction of mismatching in a PV plant located in Northern Italy”, 26th EUPVSEC, 5-9/9/11, Germany

Same module, different IV curve

Figure 2:

Three similar modules exhibiting different properties under different conditions:

- Green Line – Module IV curve under standard conditions
- Blue Line – Module current decrease at lower Irradiance
- Red Line – Module voltage increase at lower temperature



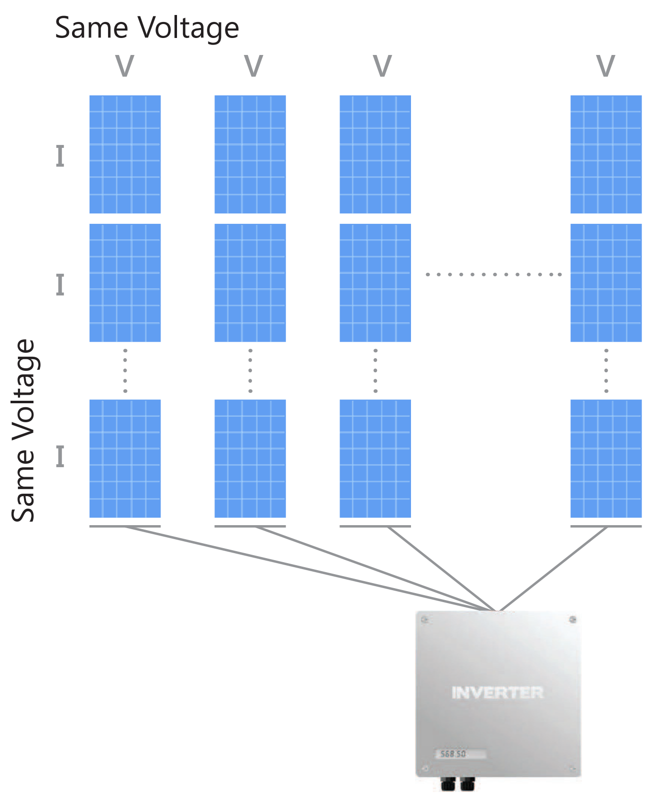
However, acting as central units, traditional inverters are by definition not able to single out the individual IV curves of modules, let alone adjust current and voltage per module. Instead, traditional inverters track the maximum power point collectively for an array of modules (figure 3). By taking a "one-size-fits-all" approach traditional inverters compromise on receiving an average system output in which weaker modules hamper the output of stronger modules in the array. The energy which is lost as a result, can commonly be referred to as module mismatch loss.

The assumption that mismatch could be avoided by creating and maintaining absolute conformity between modules throughout the entire system lifetime, seems rather impractical given the fact that even after being flash tested and sorted according to similar IV curves (power curves), a standard deviation of ±3% from the modules' nameplate capacity remains. From this point, mismatch can be aggravated by virtually anything that evokes a difference between some modules in an array.

Traditional PV Installations: One-size-fits-all

Figure 3:

The figure shows the serial connection of PV modules into strings and the connection of several strings to the inverter in parallel. All modules in the same strings receive the same current; all parallel strings receive the same voltage.

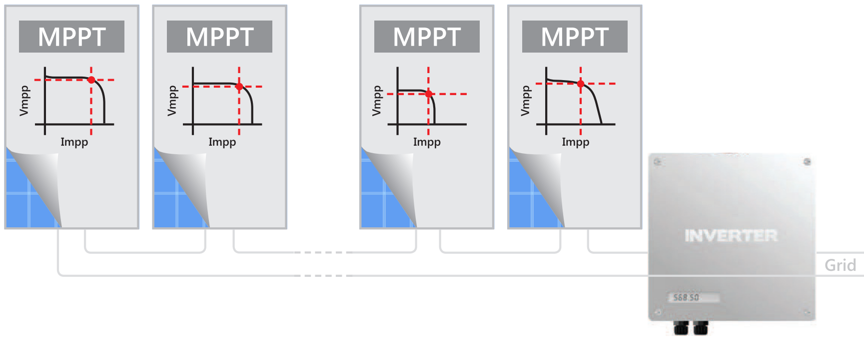


How Power Optimizers Gain Energy

Module-level MPPT adjusts the current and voltage to the specific requirements of each individual module and guarantees that modules work at their maximum capacity regardless of other modules in the string (figure 4). As opposed to an average, module-level MPPT means harvesting the sum of all peak operating points of modules which by the simple principle of math, will always result in higher energy yield than harvesting an average.

Figure 4:

Power optimizers adjust current and voltage per module in order to harvest maximum power from each module individually, removing any interdependence of modules in an array.



Six Examples

The following section will examine a set of six sample scenarios to exemplify the different levels of energy gains possible to achieve with power optimizers. From this point, mismatch can be aggravated by virtually anything that evokes a difference between some modules in an array.

1. Partial Shading – Mismatch Through Different Exposure To Light

With a little bit of imagination, the list of sources for partial shading is endless: chimneys, satellite dishes, a cable running across the installation - all can cast a bit of shadow on a module. Modules can even shade each other. By altering the intensity of light for just a few modules, partial shading diversifies the modules' output and introduces mismatch to the array. The following is an example of how much energy could be recovered for a partially shaded six kilowatt installation in Germany: The SolarEdge monitoring portal reveals that two modules, number 9 and 12, are shaded by a chimney between 08:00 and 10:00 o'clock every day (figure 5). In order to quantify the impact of shaded modules 9 and 12 on the energy production, PVsyst, a software developed at the University of Geneva, was applied to design and simulate the energy output: using a traditional 'one-size'fits-all' inverter and using SolarEdge inverters and power optimizers with individual MPP trackers for each module. The reports show that with SolarEdge, the shading loss is proportionate to the shaded area (1.5%), the traditional inverter loses 13.4% of the potential system output on the two shaded modules (figure 6). The SolarEdge system harvested 12.4% more energy in the first year of operation alone.

Figure 5:

The SolarEdge Monitoring portal displays two modules shaded by a chimney between 08:00 and 10:00 every morning. It is also interesting to see that the lower output of modules 9 and 12 does not influence the other modules in the string.

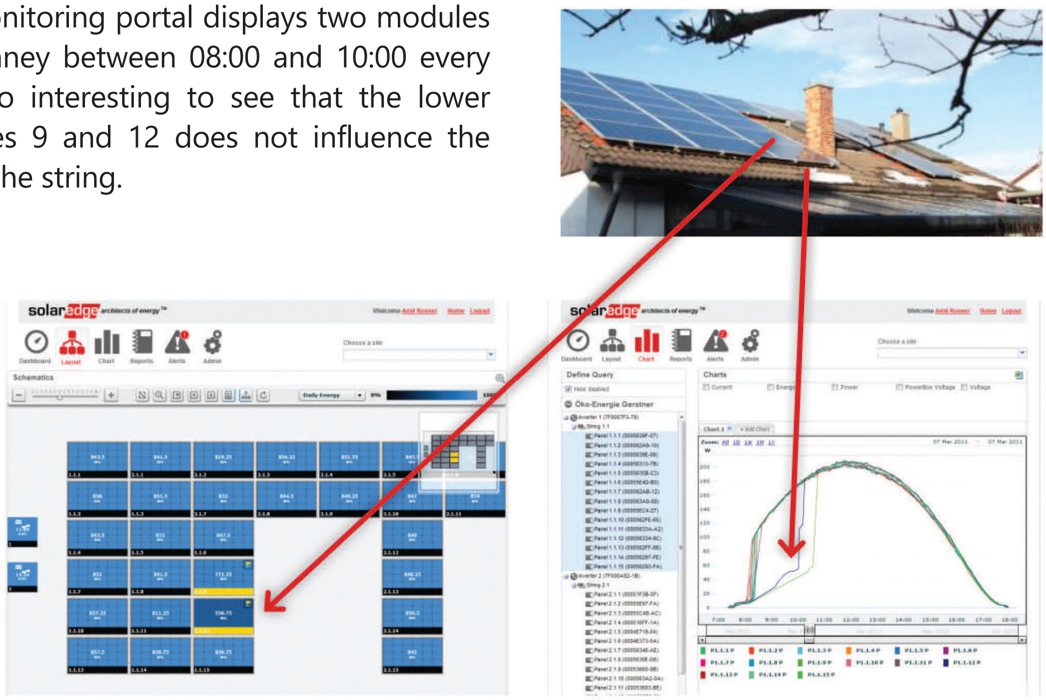
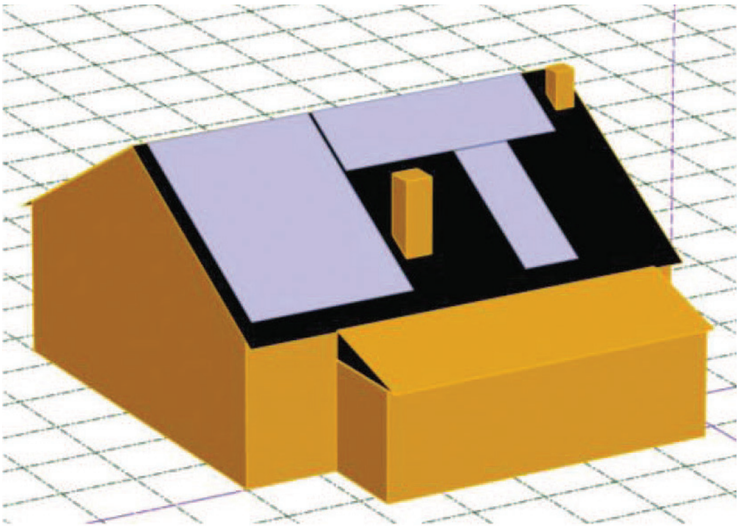
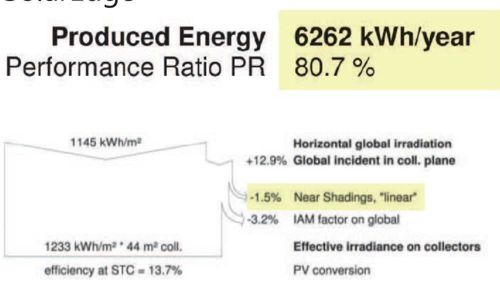


Figure 6:

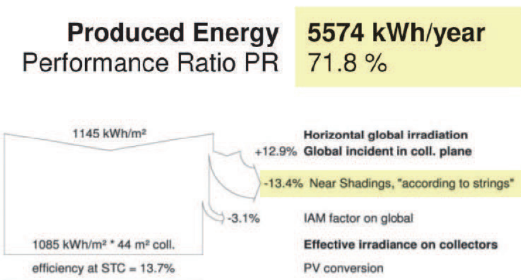
The figures show a PVsyst simulation result for a 6kW residential system which is exposed to a highly common form of shading, a chimney. Figure 6 shows the model and figure 7 shows two reports, one for SolarEdge and one for a traditional inverter system.



SolarEdge



Traditional



2. Soiling - Mismatch Through Different Exposure To Light

Another common source of mismatch loss in PV plants is module soiling. Just like partial shading, soiling is a reduction in the illuminated area of modules. Soiling can be caused by anything from falling leaves to dust and bird droppings (Images a & b). Since these factors never affect all modules equally, they create mismatch. In some locations where sand or dirt accumulate easily, the effects can be severe. Figure 7 displays a screenshot taken from the SolarEdge monitoring portal which illustrates the different outputs of soiled modules in a 700kW plant in California before it was cleaned (indicated by the different shades of blue).

Images a&b:
Two common sources of soiling: birds & sand

Figure 7:

String and module energy mismatch caused by different levels of soiling. The blue color intensity is proportional to the string daily Energy.

3. Dynamic Changes – Fast Changing Climate, Fast Changing Light

Even the most far away elements like wandering cloud fronts can act as a form of intermitted shade. Traditional inverters have difficulties detecting power fluctuations fast enough and can get stuck on local, meaning not the highest array peaks. As figure 8 and 9 demonstrate, there is reason to believe that the energy loss deriving from light-variation speed can be significant. Tracking topology is required in this condition so that it can respond fast enough to adjust current and voltage in real time as intermittencies occur. Power optimizers do exactly that. In charge of one module each, power optimizers have the ability to respond quickly and adequately to fast changes in the irradiation level.

Figure 8:

MPPT Efficiency as a function of irradiance variation speed.

Source: R. Bründlinger Austrian Institute of Technology, 4/2010

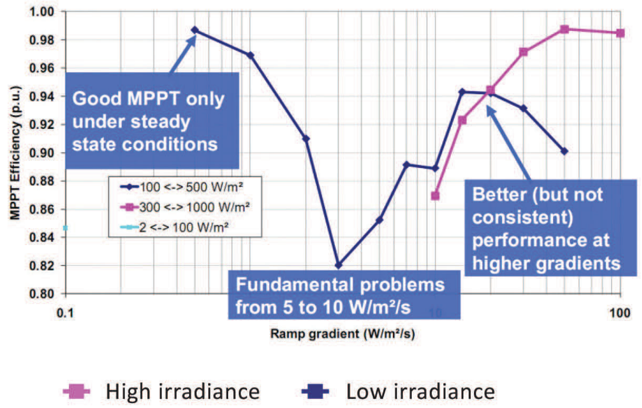
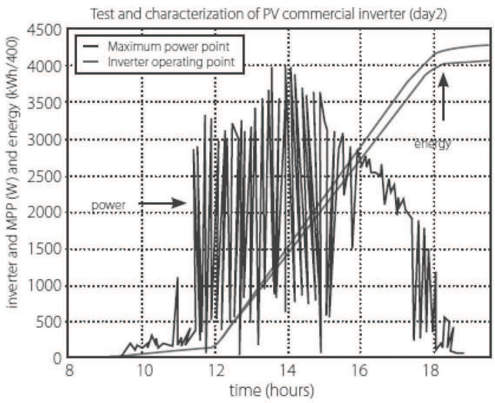


Figure 9:

Energy lost throughout a mixed weather day. The inverter-level MPP tracker shows difficulties to track the ups and downs of system output under intermitted light, shade conditions.

Source: On the Testing, Characterization, and Evaluation of PV Inverters and Dynamic MPPT Performance Under Real Varying Operating Conditions, Pablo Sanchis et al. (2007)

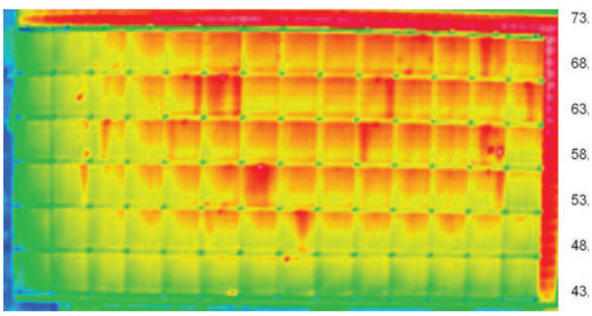


4. Different Temperatures, Different Mpps

Temperatures can drastically vary across an array. Researcher Claudia Buerhop used an infrared camera installed on a modelhelicopter to measure the different temperatures exhibited by a PV array installed in Germany. The image reveals that a temperature gradient exists within the plant. The difference in temperature measured between the top and the bottom row of modules equaled as much as 13°C with only 7,8m distance between the rows. The camera also reveals that a temperature gradient of 3-5°C even exists within particular modules. Due to the correlation between the ambient temperature and a module's output power, modules exposed to different temperatures will exhibit different power curves. Scenarios like this one occur for example, when a system is installed on a slope or on windy days when the wind picks up heat from the modules operating at one end of the array and carries the heat across the array.

Figure 10:

The figure shows an IR map of a PV field. Different modules exhibit different Vmpp requirements as a result of exposure to significantly different temperatures in the array. In addition, figure 10 shows hotspots indicating a defect in the installed module, which represents another source of mismatch.



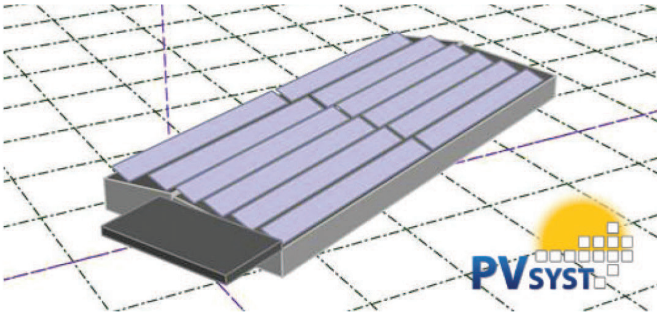
Source: C. Buerhop et al., ZAE Bayern, "The role of infrared emissivity of glass on IR-imaging of PVplants", 26th EUPVSEC, 5-9/9/11, Germany

5. Under Perfect Conditions

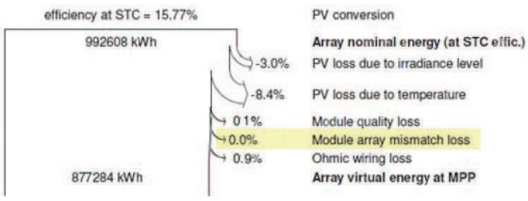
Given stable weather and that neither shading, soiling elements, a single underperforming module or temperature difference exists in a PV array, PVsyst still assumes that a standard deviation of ±3% from the modules' nameplate capacity is sufficient to result in energy loss of about 2% (figure 11). This energy retrieved from a commercial rooftop installation in California for example, for a factory with an energy consumption of 3650MWh per month on average and a tier one energy cost of 0.11 $US kWh, translates into more than $7,500 in revenue for the first year of operation alone.

Figure 11:

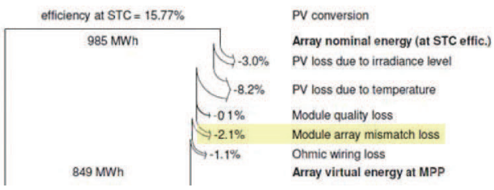
PVsyst was deployed to simulate a 475kW Rooftop design and energy output with SolarEdge inverters and power optimizers and with traditional inverters. No shading elements.



SolarEdge



Traditional

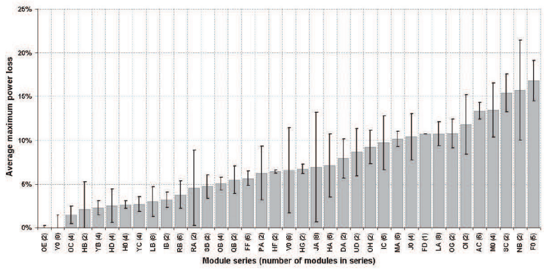


6. Aging – Mismatch As An Effect Of Time

While it is true that most modules only age to an acceptable degree of 80% of their nameplate output by the 20th year, the different rate at which they age introduces aging mismatch. Aging mismatch will increase further into the future, but research shows that it can already be regarded as a source for concern today. For example, researcher Jorge Coello attested to the degradation process of crystalline silicon modules installed in two solar power plants in Spain with 19 MW and 13 MW capacities respectively. In 2008, prior to their installation, Coello flash-tested a sample of 785 modules coming from five different manufacturers in an IEC 17025 accredited laboratory and then repeated the test in 2009 and 2010 to examine potential changes. As anticipated, the results show a mere 1.0 - 3.5% decrease in peak power within the first year and an additional 0.4 – 1.3% in the following year. More importantly however, for this purpose, is the fact that within these boundaries, modules aged at completely different rates. Over the course of two years, between 2008 and 2010, one of the five manufacturers even exhibited a variance of up to 6% between the modules. In another research released in 2009, Artur Skoczek presented results of a study on the degradation of a set of 53 different models from 20 different producers. 204 modules in total, after 19-23 years of outdoor exposure at the European Solar Test Installation (ESTI) in Ispra, Italy. The standard deviation of power reduction was more than 5% for a quarter of the module and in some cases even reached as high as 15%.

Power variance of identical modules after 20 years

Figure 12:



Black lines: Power variance of identical modules after 20 years (The figure above summarizes only the results of the betterperforming module series)

Source: A. Skoczek et. al., "The results of performance measurements of field-aged c-Si photovoltaic modules", Prog. Photovolt: Res. Appl. 2009; 17:227–240

In Conclusion

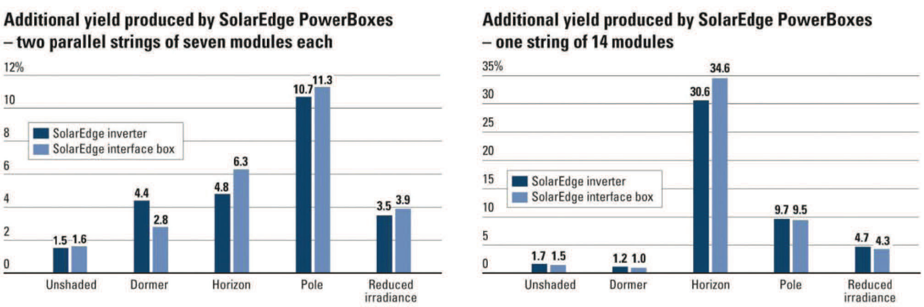
The results presented in this paper show that mismatch is an inherent state in PV arrays which is further aggravated through changes in environmental conditions. Results also show that any topology based on the underlying assumption that PV modules can eventually act as a homogenous group or that it is possible to maintain conformity between modules throughout the entire system lifetime, comes at the expense of solar PV energy output.

By applying module-level technologies, additional energy can be yielded from virtually any installation. The amount of added energy yield depends on the specific scenarios and was best summarized by PHOTON Magazine in October 2011: even under fully controlled conditions during a test performed at PHOTON Laboratories, the added energy yield with SolarEdge power optimizers ranged from 1.6% to 34% (figure 13). These results have yet to take into account other sources of mismatch established in this paper such as temperature variance, dynamic irradiance changes and aging mismatch. The uneven aging rate of modules continues to increase mismatch and reduces the return on investment of a PV system year after year.

In conclusion, as part of a joint pursuit to make PV energy output more efficient, and instead of looking at module sorting and flash testing as sustainable remedies against mismatch, the industry should become accustomed to accepting module diversity as part of the nature of PV and look at module-level power optimization as the way forward.

PHOTON Lab Test results on added energy yield of SolarEdge power optimizers

Figure 13:



The charts illustrate the added energy yield in five different scenarios which was gained adding MPPT per modules compared to a traditional inverter system with central MPPT. The bars compare SolarEdge power optimizers using a SolarEdge inverter and using a third party inverter.

Source: PHOTON Magazine, October 2011